EMISSION AND STRUCTURE OF COMPACT FIREBALLS

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The possibility that the peak of the spectral energy distribution (SED) of prompt GRB emission is produced on compact scales, prior to the acceleration of the fireball to its terminal Lorentz factor is considered. It is argued that if dissipation on these scales is associated with pair creation processes, then the observed clustering of SED peaks can be accounted for quite naturally by this mechanism. Further dissipation and processing of pairs and gamma rays at larger radii, can give rise to a nonthermal extension of the spectrum up to a rather high observed energy. If the nonthermal processes on these scales conserve the total flux of fireball quanta, then the SED peak, which is established on much smaller scales, will not be altered significantly. The asymptotic bulk Lorentz factor in this model should exceed several hundred.

1 Introduction

In popular fireball models the dissipation of the fireball kinetic energy is assumed to be accomplished through the generation of internal[1,2] and/or external[3,4] shocks. In the so-called standard internal shock model (e.g, Rees & Meszaros [1]) it is conjectured that the fireball wind, expelled by a central source of dimension $\sim 10^6$ cm, accelerates at small radii such that its Lorentz factor grows linearly with radius until the entire fireball energy is converted to kinetic energy. Temporal fluctuations in the parameters of the ejected wind then lead to formation of internal shocks in the coasting phase (i.e., the region where the wind reaches its maximum Lorentz factor), at a distance of about $r_s \simeq \Gamma^2 c\Delta t = 3\times10^{11}(\Gamma/10^2)^2(\Delta t/10^{-3}s)$ cm, where Γ is the Lorentz factor of a disturbance in the injection frame, and Δt is the variability time (i.e., the timescale over which the wind parameters fluctuate). The radiation processes commonly invoked are synchrotron and inverse Compton cooling of a nonthermal population of electrons (positrons) accelerated behind the (reverse and forward) shock fronts. Depending upon the fireball parameters, there may also be a contribution from photospheric emission and/or scattering by turbulence [5,6].

Several difficulties with the standard model have been noted in the literature: Firstly, it has been argued that the efficiency with which the fireball energy is being converted into γ-rays is expected to be discouragingly small [7,8], which seems to be inconsistent with the efficiency implied by afterglow observations. Secondly, the spectral energy distribution of GRBs peaks typically at around several hundreds keV, with relatively little scatter. This clustering of νF_ν peaks, if not due to observational selection effects as now widely believed (but cf. Dermer et al. [9]), requires fine tuning if the emission near the peak originates from a region that moves with a large Lorentz factor, as invoked in popular models [10,6]. Thirdly, the observed spectra below the SED peak appear to be steeper than predicted by the synchrotron model [11,12].

These problems have motivated reconsideration of the standard internal shock model by a number of authors. It has been shown that invoking very large variance in the Lorentz factors of different shells [13] and/or multiple shell collisions [14] may alleviate the efficiency problem. Alternatively, radiative viscosity mediated through the agency of some diffuse photons external to the fireball can also lead to appreciable enhancement of the radiative efficiency of internal shocks [15]. This may be particularly relevant in scenarios whereby the fireball is surrounded by a hot gas, as in the collapsor model [16] or the model discussed by Levinson & Eichler [17,18]. Multiple shell collisions may also give rise to a correlation between the efficiency and peak energy, with the brightest bursts clustered in the observed energy range [14], but only for certain choices of the Lorentz factor distribution of the ejected shells.

Below we consider an alternative scenario in which the SED peak of prompt emission is produced on compact scales, prior to the acceleration of the fireball to its terminal Lorentz factor.

2 The Compact Fireball Model

Preferable peak energy and high efficiency can be naturally accounted for if the emission near the peak originates from compact scales where the bulk Lorentz factor, Γ_0, is modest [10]. The requirements on the luminosity and peak energy yield the following relation between the Lorentz factor and radius of emission [10]:

$$r_0 \simeq 10^{9.5} L_{52}^{1/2} \Gamma_0 \epsilon_{300}^{-2} \quad \text{cm}, \tag{1}$$

where ϵ_{300} is the SED peak energy in units of 300 keV.

The basic picture envisioned is that at small radii, where the production time of additional gamma-rays and pairs (e.g., thermalization time) is sufficiently short, the fireball generates entropy as a result of dissipation, rather than being accelerating adiabatically as assumed in the standard model, so that the average photon energy measured in the observer frame decreases as the fireball expands. Once the average photon energy drops sufficiently below $m_e c^2$, the pair production process will taper off, at which point the SED peak is established. The fireball will then start accelerating to its terminal Lorentz factor. The radius at which the Thomson depth is roughly unity may be larger than the radius at which the SED peak is produced. Nonetheless, the emitted spectrum should not look thermal (on both sides of the peak) if dissipation persists over a range of radii that encompass the Thomson photosphere (e.g., by a shock passing through the photosphere). For example comptonization by energetic electrons (thermal or nonthermal) heated or accelerated locally, or by direct shock acceleration of photons [19] can give rise to a power law extension of the spectrum up to a very high observed energy [20,10]. If the dissipation leads only to redistribution of the fireball energy (that is, the net flux of pairs and gamma rays is conserved), then the average energy per quantum, as measured in the observer frame, will remain constant (although the radial decrement of the average energy in the fluid frame may be less steep than $1/r$). The location of the SED peak in that case should not be altered significantly. (For a photon spectrum $\propto E^{-2}$, the break (minimum) energy is smaller than the average energy by a logarithmic factor.)

Energization of the pair plasma at small scales could come from internal shocks[a] (e.g., refs [1,20,21]) but could also come from, say, collimation by surrounding baryonic material (a possibility that seems to be motivated now by several considerations). In the latter process, dissipation would proceed very efficiently when the average photon energy in the observer frame approached m_ec^2, for then large angle scattering by the walls of the collimating material of photons back into the jet, where they could appear in the local frame to be blueshifted to even higher energy, would lead to copious pair production.

The location of the Thomson sphere is limited by the baryon load. The requirement that the photospheric radius, r_{ph}, should be smaller than the radius at which the entire burst energy is converted to kinetic energy of baryons implies a mass loss rate $\dot{M} < 10^{28.5} L_{52}^{7/8} \epsilon_{300}^{-1/2}$ gr s^{-1}, $r_{ph} \leq 10^{12} L_{52}^{5/8} \epsilon_{300}^{-3/2}$ cm, and $\Gamma_{ph} \leq 300 L_{52}^{1/8} \epsilon_{300}^{1/2}$, where $\Gamma_{ph} = \Gamma(r = r_{ph})$ [10]. If the photosphere were to occur at much smaller scales, then extremely small baryon load would be implied. However, the photospheric radius may be determined by nonthermal pair cascades and may be larger than the limit set by baryonic contamination.

The maximum energy of accelerated electrons can be obtained by equating the cooling and acceleration rates. Assuming that the acceleration rate is a fraction η of the electron gyrofrequency, and denoting by η_B the magnetic field energy in units of the equipartition value yields,

$$\epsilon_{max} \simeq 1.7 \eta_B^{1/4} \eta^{1/2} \Gamma^{3/2} r_{12}^{1/2} L_{52}^{-1/4} \quad \text{GeV}. \tag{2}$$

If only the beamed gamma-rays contribute to pair productions (that is, ignoring any contribution from external photons and/or large angle scattering by a surrounding matter), then the corresponding threshold energy reads: $\epsilon_{thrs} \simeq 4\Gamma^2/\epsilon_\gamma$. Taking $\epsilon_\gamma = \epsilon_{max}$ yields

$$\frac{\epsilon_{thrs}}{m_ec^2} \simeq 10^{-3} \eta_B^{-1/4} \eta^{-1/2} \Gamma^{1/2} r_{12}^{-1/2} L_{52}^{1/4}, \tag{3}$$

which is a fraction

$$\frac{\epsilon_{thrs}}{\epsilon_{peak}} \simeq 3 \times 10^{-2} \eta_B^{-1/4} \eta^{-1/2} \tag{4}$$

of the peak energy, where it has been assumed that Γ increases linearly with radius. Consequently, efficient pair production would require $\eta_B^{1/4}\eta^{1/2} > 10^{-1.5}$ or, alternatively, the presence of an additional source of unbeamed photons.

In order to account for the observed afterglow emission, sufficient fraction of the burst energy should remain above the photosphere in the form of baryons, nonthermal pairs and/or magnetic fields. In the absence of efficient generation of nonthermal pair cascades, as described above, a transition to a magnetically dominated outflow just above the photosphere is required if the mass loss rate $\dot{M} << 10^{28.5}$ gr s^{-1} (see above), and is expected anyhow if the magnetic field energy beneath the photosphere is near its equipartition value. However, rapid pair production during the expansion of the fireball can convert a significant fraction of the energy into nonthermal pairs far enough out where the cooling and annihilation tims are long [22].

3 Conclusions

Dissipation on very compact scales, where the thermalization time or the timescale for generation of quanta by some other process is sufficiently short, can lead to an increase of the total flux

[a]It is often argued that internal shocks cannot form in the region where the wind accelerates, since in this region the Lorentz factors of different shells have the same radial variation ($\Gamma \propto r$) and, therefore, they cannot catch up. This is not necessary true if the wind profile deviates from conical (as one might expect in the case of collimation), or if different shells satisfy different boundary conditions, as, e.g., in the case wherein shell ejection occurs over a range of radii or if the shells are oblique.

of fireball quanta, and a consequent reduction of the observed energy per quantum. This can give rise to a preferable peak energy below $m_e c^2$, particularly if effective dissipation on these scales is associated with some pair creation processes; as an example we proposed large angle scattering of gamma rays from a jetted fireball back into the jet, by baryon rich wind surrounding the jet. Additional dissipation and processing of fireball quanta at larger radii, for instance by shocks moving along the ejecta, would result in further evolution of the fireball spectrum and, ultimately, the formation of nonthermal extension up to a rather high observed energy. The location of the νF_ν peak might be affected by this additional dissipation, but only slightly (roughly a logarithmic factor) if the flux of quanta is roughly conserved.

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